Restricted Circulation

This paper is not an official document: it is for information only and reference cannot be made to it in any printed publication without the permission of the author.

AGRICULTURAL MEMORANDUM NO 512

Crop production in higher latitude, maritime regions

by R W Gloyne

II. Total ("global") solar radiation and net radiation or radiation balance

1. Total ("global") solar radiation

The essential features of the pattern of average annual "global" solar radiation (in K cals cm^{-2} $year^{-1}$) over the world are illustrated in Fig 1. In addition, for selected stations in the northern hemisphere, average annual and monthly mean daily values (g cals cm^{-2} day^{-1}) and the annual totals are given in Table 1.

Fig 1 (from Budyko 1968) requires significant amendments on a sub-regional and country-wise scale (as evidenced by reference to details in Table 1). For the British Isles and adjacent regions a more accurate spatial pattern is given by Day (1961) of which Figs 2 and 3 are examples (1 gr cal≡1.16 mW hrs). Nevertheless, the broad global scale representation of Fig 1 remains valid. Amongst its most striking features are:

(i) the relatively open zonal gradient polewards from 50°N compared with that towards the equator.

leading to:

(ii) the high total in inland arctic and polar regions.

(iii) the marked southward plunge of the isopleths in the mid and eastern Atlantic. This results, for example, in an annual income at Lerwick (60° 08'N; 1° 11'W) of 67 K cals cm^{-2} yr^{-1}, less than that at the same latitude in Scandinavia (Bergen 60° 24'N; 5° 19'E of 71 K cals cm^{-2} yr^{-1} Oslo 59° 56'N; 10° 44'E of 76 K cals cm^{-2} yr^{-1}). Indeed in Lapland (Sodankyla 67° 22'N; 21° 56'E) the corresponding figure is 69 whilst at Barrow in Alaska (71° 18'N; 155° 47'W) it is 77. Eskdalemuir (55° 19'N; 3° 12'W), in inland southern

Scotland, returns a figure of 70 K cals cm^{-2} yr^{-1} - appreciably below the 74 and 88 K cal cm^{-2} yr^{-1} respectively for Reykjavik (64° 09'N; 21° 56'W) and Copenhagen (55° 41'N; 12° 32'E). However from Figs 2 and 3 it is clear that areas in Scotland either side of the wide central core received appreciably greater radiation incomes than indicated by Eskdalemuir.

(iv) the run of the 80 K cal cm^{-2} yr^{-1} in the southern hemisphere is also worthy of note.

Important latitudinal contrasts are clearly evident in relation to seasonal distribution. In the "summer half-year" (i.e. April-September inclusive) polar regions enjoy higher radiant income than many areas between 50° and 55° N. Taking the values for June as illustrative, McKay, Findlay and Thompson (1970) indicate an average daily input exceeding 600 gr cals cm^{-2} in a large area north of 70°N, and (see Table 1) of 545 gr cals cm^{-2} at Barrow Alaska. Moving southwards we find a value for June in favoured areas of the British Isles (Aberporth on the coast of Wales, 52° 08'N: 4° 34'W Manley (1970) of 494 gr cals cm^{-2}). For Copenhagen the corresponding total is 506 gr cal cm^{-2} whilst at Kew (London) the quoted figure is 415 (Manley 1970). Of the sample of places chosen, the two Scottish stations (Lerwick and Eskdalemuir) return the lowest values for the month of June (see (iii) above for some reservations on the "representativeness" of Eskdalemuir observations).

Clearly the high values of poleward areas in summer must be partly attributed to greater day-length. It should however be noted that the inputs quoted - being those on a horizontal surface - are nevertheless achieved in spite of the relatively low solar altitude during the polar day.

Table 1 and Fig 1 reveals an annual energy input which varies relatively narrowly ($\pm$10 K cals cm^{-2}) about a mean of 70 K cals cm^{-2} over a latitudinal range of 55°N (and approximately 50°N) to beyond the Arctic Circle.

Within this annual total there are large differences in seasonal distribution (associated with latitude) and as between different meridians depending largely on whether these run over extensive stretches of water or over land surfaces - the tighter gradient being in lower latitudes over the sea and higher latitudes over the land. In

the summer half-year, stations inland on the continental mainland north of the Arctic Circle have inputs comparable with those of regions much further south; coastal sites e.g. Tromso have appreciably lower inputs.

2. Net radiation or radiation balance

The net flux of radiation (R(n)) to the surface is given by

$$R(n) = (1 - \alpha)Q + L(d) - L(u)$$

where

Q = global (sun + sky) i.e. "short-wave" radiant flux to the surface

L(d) = downward flux of "long-wave" radiation from the atmosphere and clouds

L(u) = upward flux of "long-wave" radiation from the ground surface to the atmosphere

($L(u) \geq L(d)$ with important, but infrequent exceptions)

α = reflection coefficient of ground surface for "short-wave" radiation ("albedo").

Typical values of α for different surfaces are:

(i) open water: varies with solar altitude, but a time-average is 0.05 to 0.07

(ii) green vegetation: 0.25

(iii) forests: may be as low as 0.10, but more generally $0.10 \leq \alpha \leq 0.20$

(iv) fresh snow: 0.75 to 0.95

old snow: 0.40 to 0.70

(for a comprehensive list see Sellers 1966 p21).

Clearly an extensive snow cover materially alters α and hence R(n), and this change significantly contributes to the sharp transition between arctic and polar climates on the one hand, and temperate climates on the other (see Fig 4 and Table 2). As a first approximation, if areas north of (say) 70°N are omitted then in the regions under examination, all places appear to enjoy net radiant incomes during a 6 month period which - as already noted for global radiation - differ less than might well be expected.

Clearly however place-to-place variations within the "summer" half-year, the ratio of the direct to diffuse components and solar geometry may well be found very significant in relation to the utilisation of such energy by various crop stands. Sharp contrasts with latitude are however evident in winter and these materially influence the annual total: even so the relatively small variation within the latitudinal band 50-60°N deserves mention.

3. Relationships between gross means of R(n) and Q

The relationship between net radiation and incoming solar radiation has been extensively examined in recent years. R(n) obviously depends upon α, but incoming radiation can be expressed either as Q (i.e. the global total) or $Q(1 - \alpha)$ (i.e. that absorbed by the ground surface). Both approaches are of interest in different situations.

Relationships have been derived:

for the complete 24 hours.

for daylight hours - on an hourly or minute-to-minute basis.

3.1 Results obtained using data for the 24 hour day

Since most of the readily available data and estimates of R(n) and Q are expressed in terms of daily (24 hr) totals, general regional and global comparisons are most conveniently undertaken on this basis. In Table 3 the ratios R(n): Q (24 hr basis) are set out for a selection of stations mentioned in Tables 1 and 2: months with a negative value of R(n) are omitted. Perhaps the most striking result is the equality of ratios over a wide latitudinal span for the summer months of the year.

Fitzpatrick and Stein (1970) present 24 hour ratios of R(n): Q for:

(i) a well-irrigated cotton crop in a tropical dry monsoonal climate (Kunuurra, Australia. 15° 24'S 128° 36'W)

and (ii) a non-irrigated pasture in a humid mid-latitude environment (New Jersey USA. 39° 34'N 75° 10'W) (for the "growing season" only, i.e. March - October).

In the course of the work, highly significant linear relationships were found between monthly means of R(n) and Q if days were categorised according to atmospheric clarity - defined as the ratio:

$$\frac{Q\ (\text{surface})}{Q\ (\text{extra terrestrial})}$$

The associated values of R(n)/Q range from 0.35 to 0.69 with a mean of 0.55 - a value similar to that obtained by Monteith et al (1962) and Stanhill et al (1966).

Monteith (1965) quotes some values for Hamburg during the 6 summer months (1954 - 1963) giving a mean of 0.55 with 0.56 (in 1954: a very cloudy year) and 0.54 (in 1959: a very sunny year).

Data for an "alpine tundra" in mid July (the White Mountains in California 37° 33'N: 118° 14'W at 3580 m) gives a ratio of 0.55 (Terjung W H, Kickart R N, Potter G L, Swarts S W 1969).

4. The statistical relationship between R(n) and Q

4.1 The relatively sophisticated equipment needed to study day-time radiation fluxes has been exploited:

(i) to examine relationships with short averaging period (e.g. minutes, hours).

(ii) to incorporate the effects of albedo, and hence the value of $Q(1 - a)$ - the net short wave input.

A few results are given below:

(a) Monteith and Szeicz (1961)

$$R(n) = 0.82(1 - a)Q - 5.9 \text{ gr cals cm}^{-2}\text{hr}^{-1}$$

(Cloudless days in E England).

(b) Monteith et al (1962)

$$R(n) = 0.92(1 - a)Q - 0.11 \text{ gr cals cm}^{-2}\underline{\text{min}}^{-1}$$

(Fine, clear summer days)

(c) Davies and Buttimor (1969)

$$R(n) = 0.93(1 - a)Q - 0.13 \text{ gr cals cm}^{-2}\text{min}^{-1}$$

A reasonable value of a for a green surface is 0.23 and hence:

$$R(n) \rightarrow 0.72Q - 0.13 \text{ (gr cals cm}^{-2}\text{min}^{-1}\text{)}$$

A coefficient of about 0.90 when a appears explicitly is quite typical for many cases quoted in the literature.

4.2 The opportunity was taken to check on the adequacy of the linear relationships between data for Q and R(n) (24-hour basis) for sites of immediate interest (viz 3 in

British Isles: Kew, Eskdalemuir and Lerwick, and 3 in Scandinavia: Bergen, Stockholm and Copenhagen). The basic data were period monthly averages of mean daily Q and R(n) (much scatter is obviously already eliminated by the averaging process). Figure 5 for Bergen and Lerwick is given for illustration together with linear regressions for all 6 stations (Fig 6). The statistical details are set out in Table 4.

Table 4. Statistical parameters for the linear regression

$$R(n) = a\,Q + b$$

for selected stations. Based upon period monthly mean daily values

(units gr cals $cm^{-2}day^{-1}$)

Station	a	b	$r(R(n):Q)^2$	R(n)/Q (annual means)
Scandinavia				
Bergen	0.79	-100	0.986	0.28
Stockholm	0.72	- 89	0.989	0.28
Copenhagen	0.66	- 65	0.988	0.39
Great Britain				
Lerwick	0.74	- 77	0.998	0.32
Eskdalemuir	0.70	- 87	0.990	0.32
Kew	0.61	- 62	0.991	0.33

Some insight into the physical processes leading to the linear relationship between R(n) and Q may be derived from the concept of a "heating coefficient" ($\bar{\beta}$) suggested by Monteith and Szeicz (1961) and developed for clear sky day-time conditions.

The energy balance at the surface is defined by:

$$R(n) = (1 - \alpha)Q + L \qquad (L = \underline{\text{net}} \text{ long-wave input})$$

whilst empirically we find:

$$R(n) = a(1 - \alpha)Q + b$$

A condition for the consistency of these equations can be expressed as:

$$R(n) = \frac{1 - \alpha}{1 + \bar{\beta}} Q + L(o)$$

where $\bar{\beta}$ = the "heating coefficient" and is the increase in net long-wave (terrestrial) radiation loss per unit increase in net radiation

and $L(o)$ = the amount of long-wave radiation that would be lost during daylight by a surface at the mean air temperature for the whole day.

For green crops β lies between 0.15 and 0.25, for bare soil 0.35–0.45 whilst L(o) is between -5 and -10 cal $cm^{-2}hr^{-1}$. Thus for each unit increase in R(n) at the surface,

there is a net loss of about 0.20 units by long-wave exchange (the immediate cause of this increased loss is the rise of surface temperature consequent upon the increase of the R(n) input).

The relations quoted in Table 4 and illustrated in Figs 5 and 6 are for radiant fluxes operating over complete 24 hour period and hence not identical with the situation to which the equations above refer.

The linearity of the relationship is preserved when R(n) is negative and there is an increase net loss of energy as the total external input decreases.

The meaning and validity of the "heating coefficient" β and its more general adoption under other than clear sky conditions still appear matters of controversy e.g. Idso (1968), Stanhill et al (1966), Davies and Buttimor (1969): but these matters lie outside our immediate concern.

References

Brown J (1970) "Environmental Setting, Barrow, Alaska" Proc Conf on Productivity and Conservation in N Circumpolar Lands. p50. IUCNN. Switzerland. 1970.

Budyko M I (1968) "Solar radiation and the use of it by plants" Proc Reading Symp on "Agroclimatological Methods" p39-54. UNESCO. Paris.

Davies J A (1967) "A note on the relationship between net radiation and solar radiation" Quart J Roy Met Soc 93 pp109-115.

Day G J (1961) "Distribution of total solar radiation on a horizontal surface over the British Isles and adjacent areas" Met Mag 90. 1961. p269-284. London. HMSO.

(Davies J A and (Buttimor P H (1969) "Reflection coefficients, heating coefficients and net radiation at Simcoe, Southern Ontario" Agr Meteorol. 6(1969). pp373-386.

Einarsson M A (1969) "Global radiation in Iceland" Icelandic Meteorological Service. Reykjavik. 1969.

(Findlay B F and (Thompson H A (1970) Proc Conf on Productivity and Conservation in N Circumpolar Lands. pp 10-33. IUCNN. Switzerland. 1970.

(Fitzpatrick E A and (Stern W R "Net radiation estimated from global solar radiation" Symp on Plant Response to Climatic Factors. 1970. UNESCO. (To be published).

Idso S B (1968) "An analysis of the heating coefficient concept" J Appl Met. 7. p716-717. USA. Aug 1968.

Johannesson T W (1970) "Climates of Northern and Western Europe" Vol 5. World Survey of Climatology. Elsevier Pub Co.

Manley G (1970) "Climates of Northern and Western Europe" (p100) Vol 5 of World Survey of Climatology. Elsevier Pub Co.

McKay G A "A Climatic Perspective of Tundra Areas".

Monteith J L (1965) "Radiation and crops" Exp Agr Rev 3. in Expl Agric (1965) 1 pp241-251.

(Monteith J L and (Szeicz G (1961) "The radiation balance of bare soil and vegetation" Quart J Roy Met Soc, 81. 1961. p159-170.

(Monteith J L and (Szeicz (1962) "Relative temperature in the heat balance of natural surfaces" Quart J Roy Met Soc. 88. p496-507.

Roach W T (1955) Air Ministry, Met Res Ctee. MRP No 936.

Sellers W D (1965) "Physical Climatology" Univ Chic Press. ppVIII + 272.

(Stanhill G, (Hofstede G J and (Kalma J D (1966) "Radiation balance of nature and agricultural vegetation" Quart J Roy Met Soc. 92. pp128-140.

(Terjung W H, (Kickert R N, (Potter G L and (Swarts S W (1969) "Energy and moisture balance of an alpine tundra in mid-July" Arctic & Alpine Res. 1(4). 1969. pp247-266.

Table 1. Global radiation: mean daily values by months at selected "high" latitude stations in the Northern Hemisphere

Place	Mean daily values. gr cals $cm^{-2}day^{-1}$													Average yearly total k cals $cm^{-2}yr^{-1}$
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	
Barrow (a) 71°18'N. 156°47'W	2	39	177	390	527	545	437	262	120	41	5	0	212	77.4
Tromso (b) 69°39'N. 18°57'E	0	21	103	216	294	401	397	237	120	41	5	0	153	56.0
Karasjok (b) 69°28'N. 25°31'E	0	22	121	248	363	437	415	271	123	46	4	0	172	62.7
Sodankyla (b) 67°22'N. 26°39'E	3	43	153	312	372	445	452	284	136	51	10	-	189	69.0
Reykjavik (c) 64°09'N. 21°56'W	12	53	164	289	431	412	438	351	180	81	21	4	203	74.4
Trondheim (b) 63°25'N. 10°27'E	17	54	157	263	413	411	436	313	184	90	26	9	199	72.6
Lerwick (d) 60°08'N. 1°11'W	23	69	145	267	343	399	358	277	179	86	32	14	183	66.8
Bergen (b) 60°24'N. 5°19'E	29	67	168	251	426	400	371	297	172	97	38	16	195	71.2
Oslo (b) 59°56'N. 10°44'E	26	74	189	292	434	422	396	300	182	113	32	16	207	75.6
Stockholm (b) 59°21'N. 18°04'E	27	81	179	208	374	442	408	328	210	102	41	19	209	76.1
Helsinki (b) 60°10'N. 24°57'E	19	70	197	291	401	478	449	304	187	83	23	12	210	76.7
Eskdalemuir (d) 55°19'N. 3°12'W	54	96	163	266	349	383	316	272	204	116	56	34	193	70.3
Copenhagen (b) 55°41'N. 12°33'E	49	108	205	325	438	506	448	347	267	129	48	32	242	88.5
Kew (d) 51°28'N. 0°19'W	51	90	187	268	372	415	376	320	244	141	66	37	214	78.3

(a) Brown J (1970)
(b) T Werner Johannessen (1970)
(c) Einarsson M A (1969)
(d) Manley G M (1970)

See References

Table 2. Mean values of net radiation

(i) for individual months
(ii) for "summer half-year" (Apr–Sep) inclusive
(iii) for year
in terms of gram-cals $cm^{-2} day^{-1}$
and (iv) yearly total (in k-cals $cm^{-2} yr^{-1}$)

Place		Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Apr–Sep	Year	Year K cals $cm^{-2} yr$
		(in gr-cals cm^{-2} day^{-1})										
Tromso	(a)	-72	-24	63	219	211	101	2	-64	96	3	1.1
Karasjok	(a)	-84	-36	105	222	201	100	-4	-76	99	2	0.8
Trondheim	(a)	-57	48	168	225	231	142	46	-39	144	31	11.2
Lerwick	(b)	31	122	171	215	199	131	62	-11	150	59	21.7
Bergen	(a)	9	102	223	221	201	141	64	-11	159	55	20.0
Oslo	(a)	-27	107	227	231	213	141	56	- 7	163	54	19.6
Stockholm	(a)	17	41	180	256	204	144	59	-13	148	62	22.8
S Finland	(a)	- 7	87	197	317	265	152	53	-39	179	58	21.1
Eskdalemuir	(b)	37	106	152	196	162	127	70	13	135	61	22.2
Copenhagen	(a)	55	151	223	275	247	167	97	19	194	96	35.0
Kew	(b)	39	110	156	196	178	136	86	17	144	67	25.4

(a) T Werner-Johannessen (1971)

(b) Met Office London. Lerwick and Eskdalemuir 1964–68 (incl)
Kew 1963–70 (incl)

Table 3. Ratio of mean values (monthly basis) of Rn (Table 2) to Q (Table 1) for selected months of the year (i.e. entries omitted when Rn is negative

Place	Apr	May	Jun	Jul	Aug	Sep
Tromso	..	0.21	0.55	0.53	0.42	..
Karasjok	..	0.29	0.51	0.48	0.37	..
Trondheim	0.18	0.41	0.55	0.53	0.45	0.25
Lerwick	0.46	0.50	0.54	0.56	0.47	0.35
Bergen	0.41	0.52	0.55	0.54	0.47	0.37
Oslo	0.37	0.52	0.55	0.54	0.47	0.31
Stockholm	0.20	0.48	0.58	0.50	0.44	0.28
S Finland	0.30	0.53	0.66	0.59	0.50	0.28
Eskdalemuir	0.40	0.44	0.51	0.51	0.47	0.34
Copenhagen	0.46	0.51	0.54	0.55	0.48	0.36
Kew	0.41	0.42	0.47	0.47	0.43	0.35

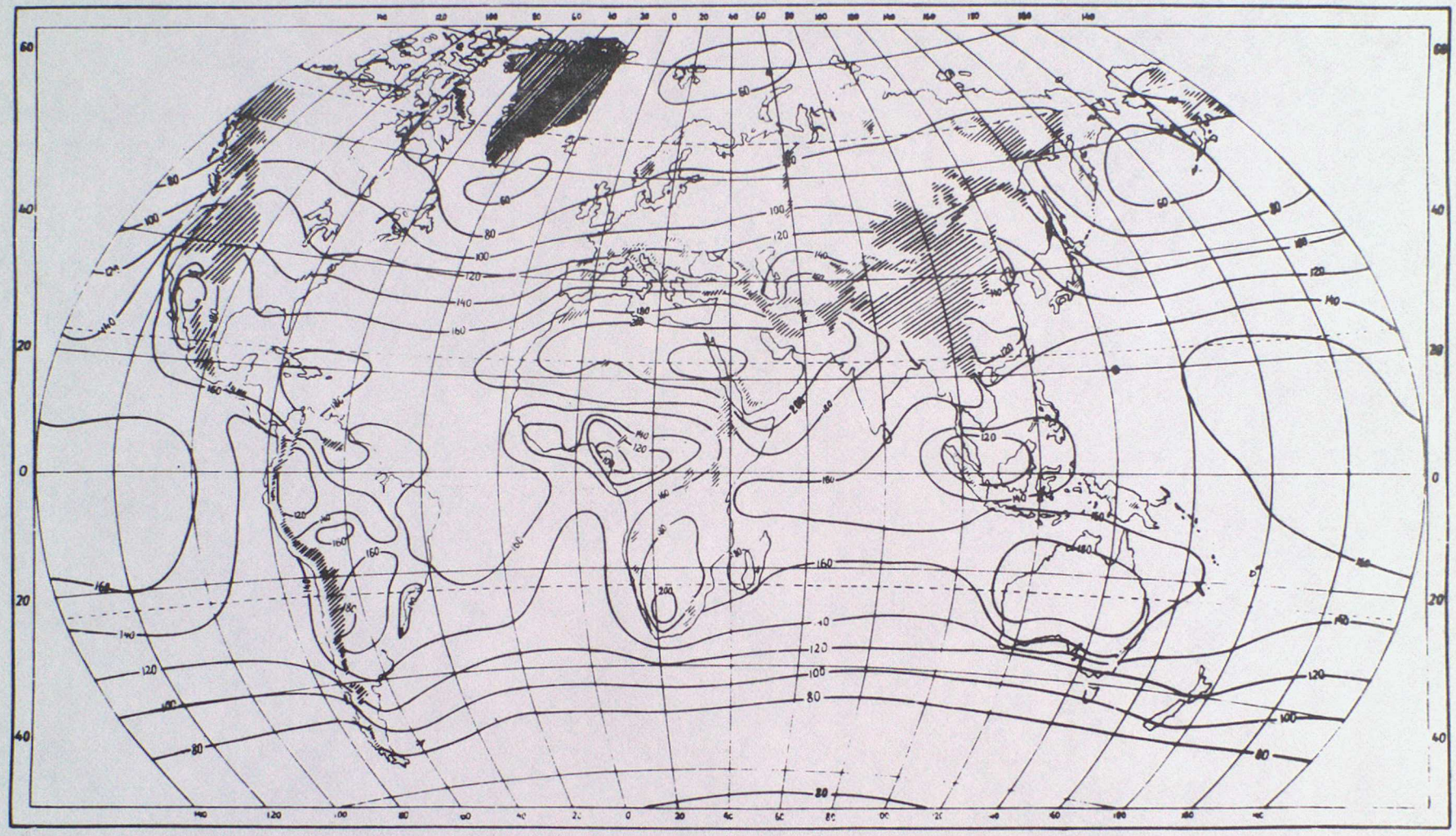

Fig 1. Total (global) radiation. Year (K cals/cm^2 year) (from Budyko 1968)

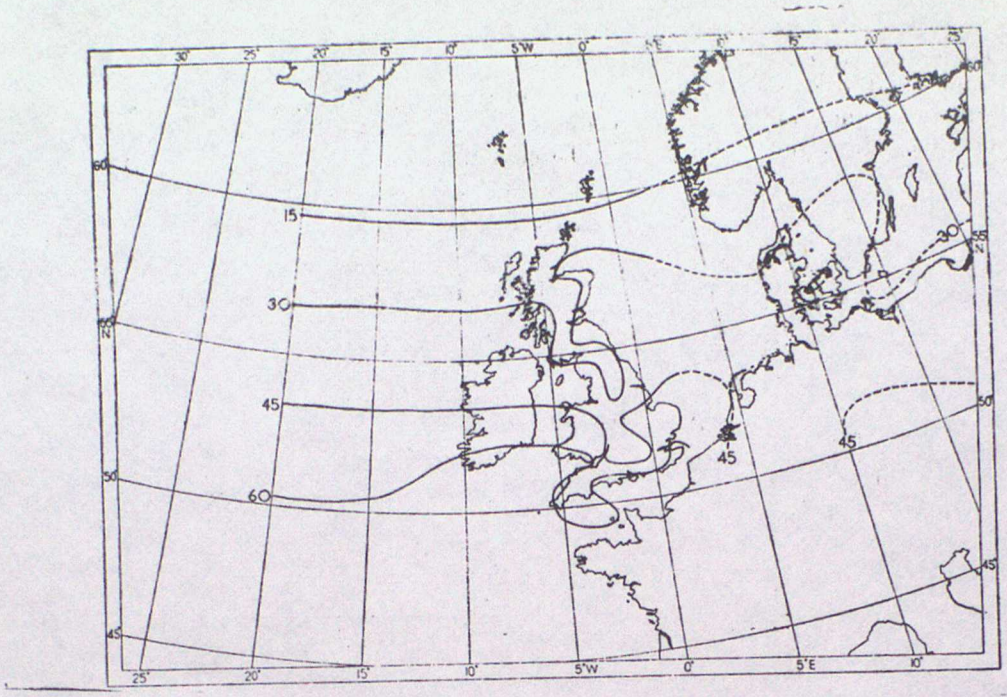

Fig 2. Isopleths of mean daily total of global solar radiation (mWhr cm^{-2} day^{-1}) for December (Day 1961)

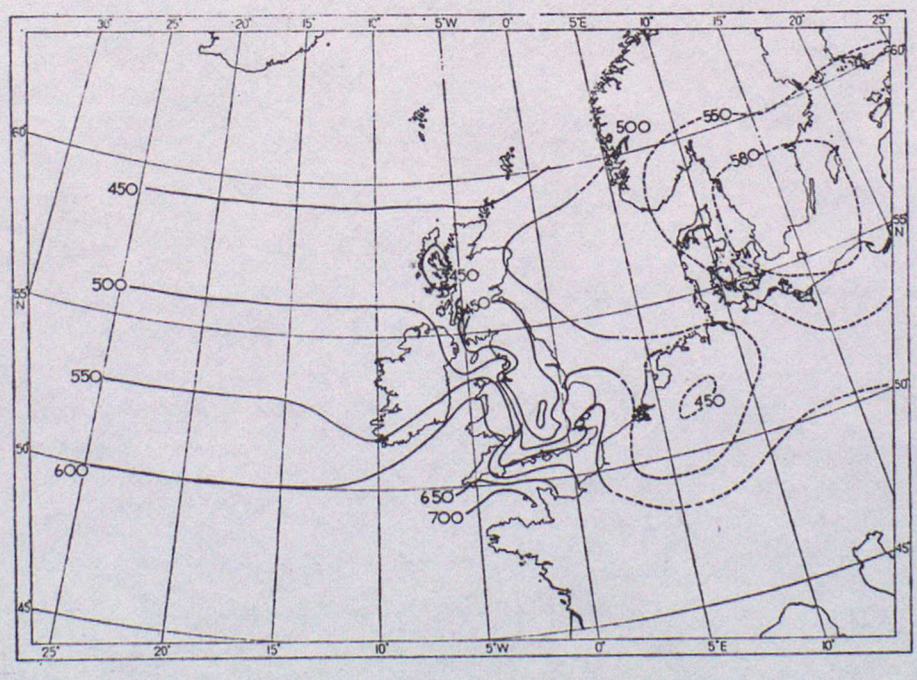

Fig 3. Isopleths of mean daily total of total solar radiation (mWhr cm^{-2} day^{-1}) for June (Day, 1961)

RE 16408 TBL(23)

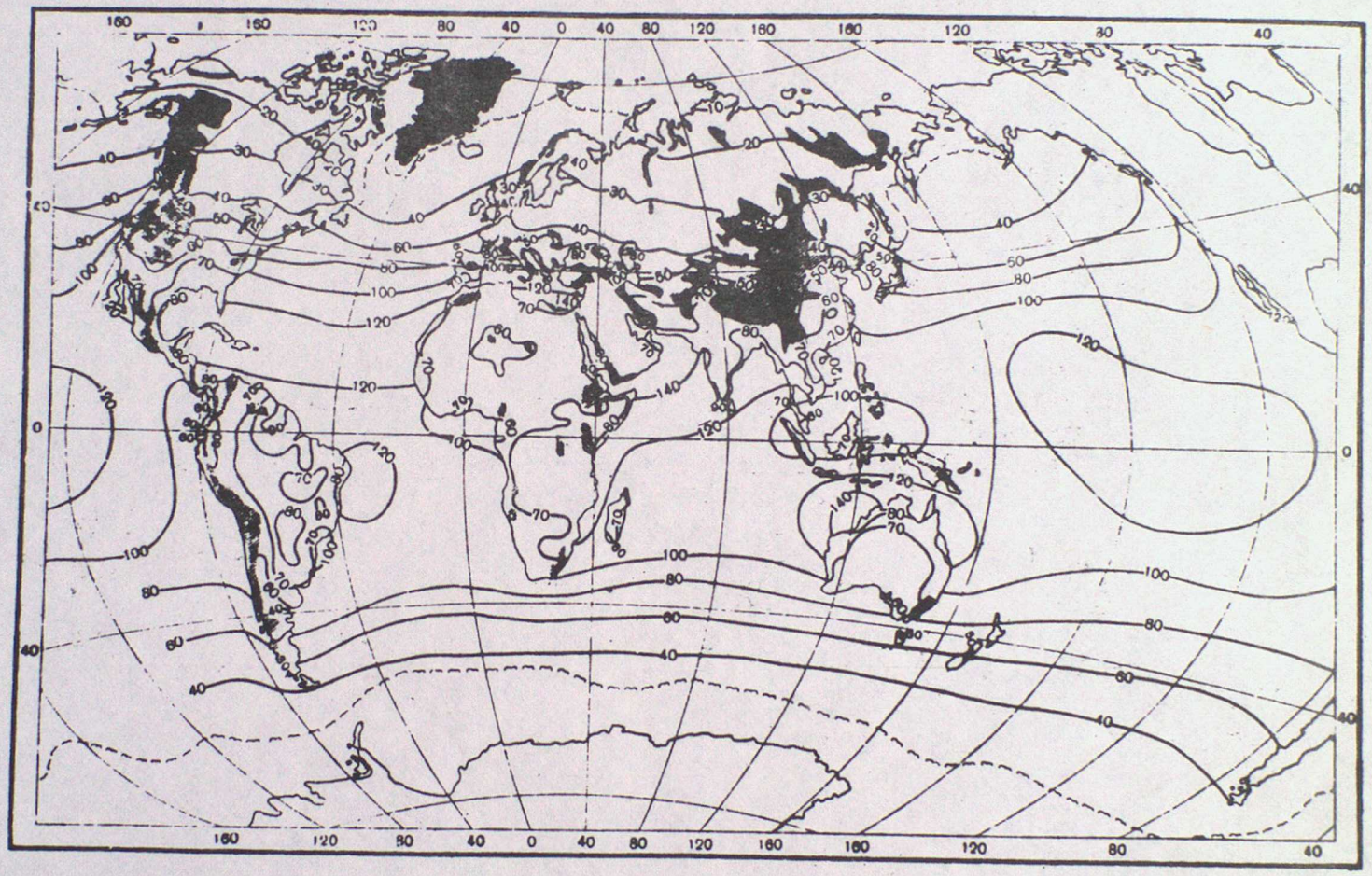

Fig 4. Radiation balance. Year (k cals/cm^2 yr) (from Budyko 1968)

RE 16408 TBL(25)

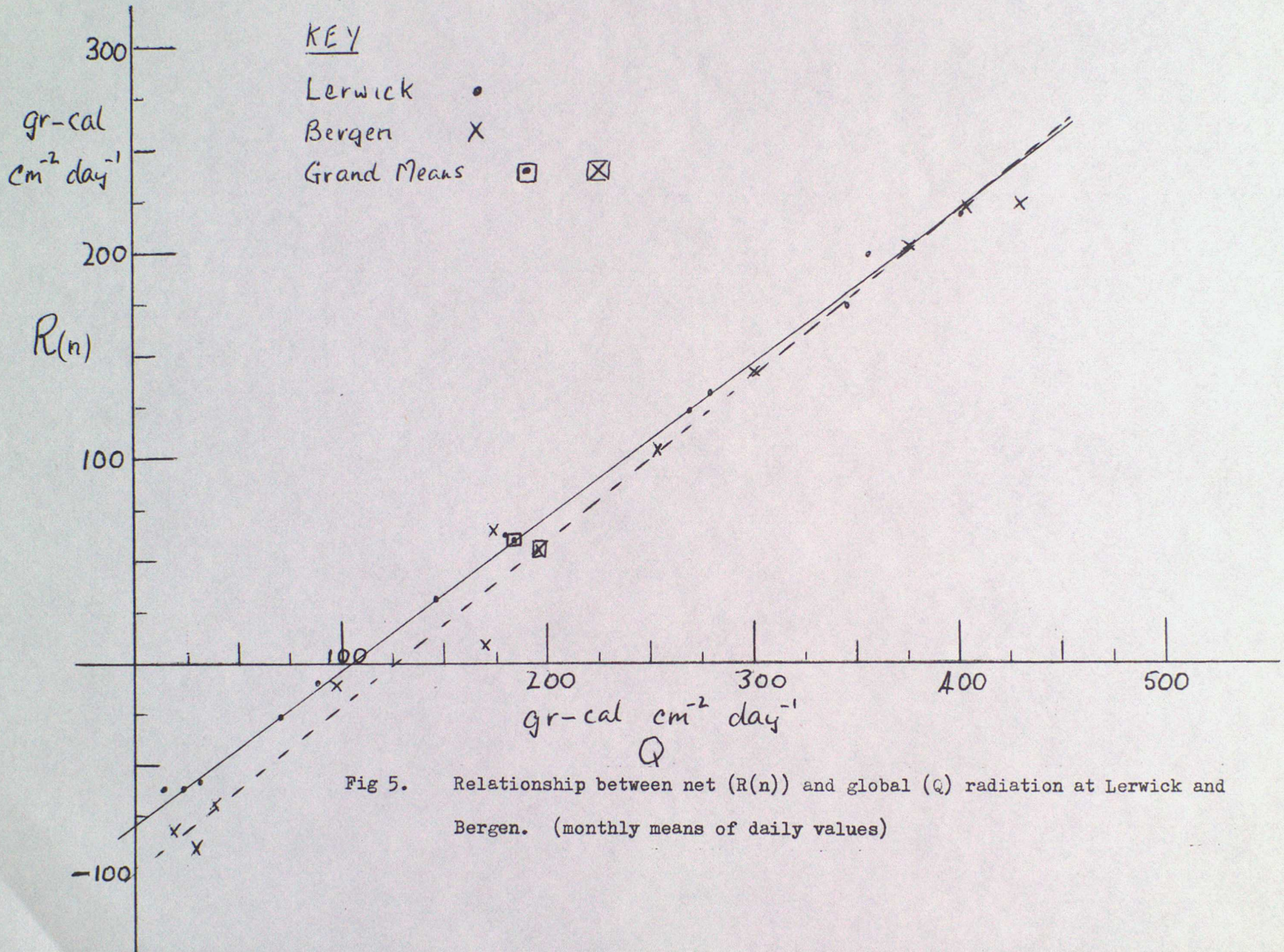

Fig 5. Relationship between net (R(n)) and global (Q) radiation at Lerwick and Bergen. (monthly means of daily values)